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Ascheman

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(54) **METHODS FOR TRANSMEMBRANE MEASUREMENT OF OXYGEN CONCENTRATION AND MONITORING CHANGES IN OXYGEN CONCENTRATION WITHIN A SPACE ENCLOSED BY A MEMBRANE EMPLOYING A PHOTOLUMINESCENT TRANSMEMBRANE OXYGEN PROBE**

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USPC 436/138, 135, 127; 73/1.06, 1.02, 1.01
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(57) **ABSTRACT**

Measuring oxygen concentration and monitoring changes in oxygen concentration within an enclosed space by applying a transmembrane photoluminescent oxygen probe to the external surface of the membrane forming the enclosed space, wherein the transmembrane photoluminescent oxygen probe has an oxygen impermeable support layer carrying a spot of an oxygen-sensitive photoluminescent dye and a layer of a pressure-sensitive adhesive on a first major surface of the support layer.

10 Claims, 1 Drawing Sheet

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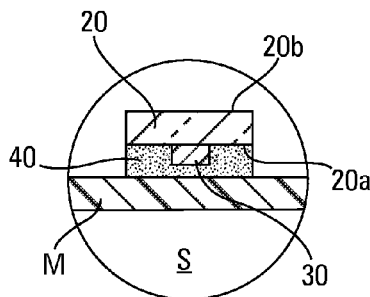
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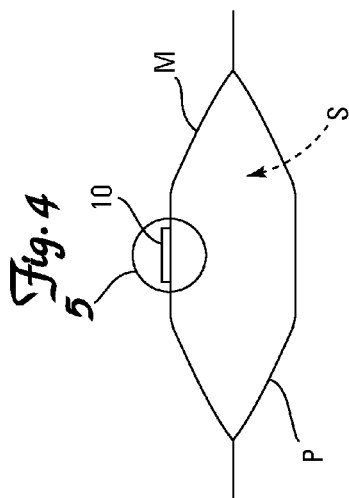
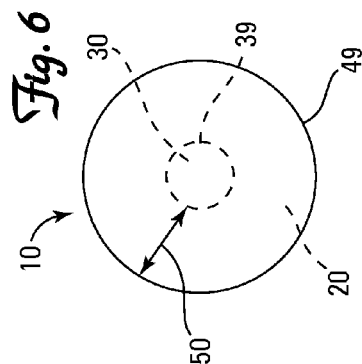
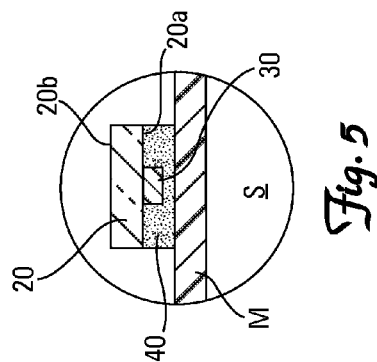
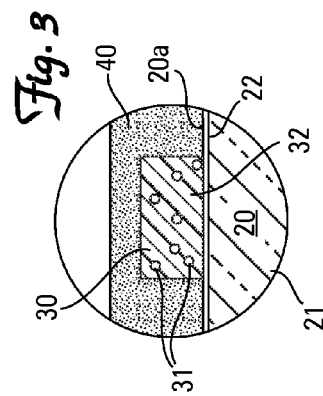
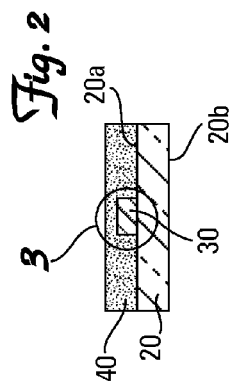
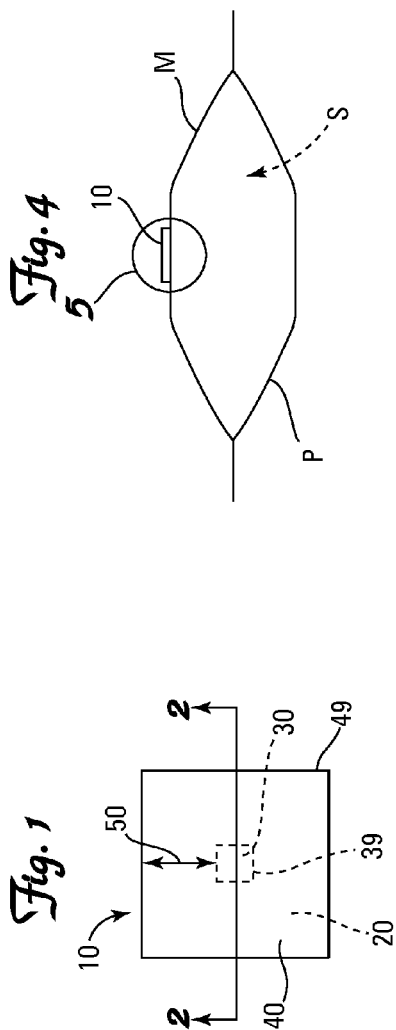
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**METHODS FOR TRANSMEMBRANE
MEASUREMENT OF OXYGEN
CONCENTRATION AND MONITORING
CHANGES IN OXYGEN CONCENTRATION
WITHIN A SPACE ENCLOSED BY A
MEMBRANE EMPLOYING A
PHOTOLUMINESCENT TRANSMEMBRANE
OXYGEN PROBE**

BACKGROUND

Solid-state polymeric materials based on oxygen-sensitive photoluminescent dyes are widely used as optical oxygen probes. See, for example United States Published Patent Applications 2009/0029402, 2008/8242870, 2008/215254, 2008/199360, 2008/190172, 2008/148817, 2008/146460, 2008/117418, 2008/0051646, 2006/0002822, U.S. Pat. Nos. 7,569,395, 7,534,615, 7,368,153, 7,138,270, 6,689,438, 5,718,842, 4,810,655, and 4,476,870. Such optical probes are available from a number of suppliers, including Presens Precision Sensing, GmbH of Regensburg, Germany, Oxsense of Dallas, Tex., United States, and Luxcel Biosciences, Ltd of Cork, Ireland.

Such probes may be interrogated through many common packaging materials and therefore allow nondestructive measurement of the oxygen concentration within an enclosure by simply incorporating a probe within the packaging, typically adhered to the inside surface of the cover. Unfortunately, there are certain applications where incorporation of such a probe into the packaging is not acceptable—such as packages made from materials that interfere with interrogation of the probe, packages in which the presence of such a probe inside the packaging may be mistakenly perceived by consumers as an undesired contamination of the packaged product, or packages whose per package value or profit margin cannot accommodate the cost of incorporating a probe into every package or tracking those containing a probe when only select packages include a probe.

Hence, a need exists for a probe that can nondestructively sense the oxygen concentration within an enclosure from outside the enclosure.

SUMMARY OF THE INVENTION

A first aspect of the invention is a transmembrane photoluminescent oxygen probe comprising an oxygen impermeable support layer carrying a spot of an oxygen-sensitive photoluminescent dye and a layer of a pressure-sensitive adhesive on a first major surface. The photoluminescent dye is preferably embedded within an oxygen-permeable hydrophobic polymer carrier.

A second aspect of the invention is a method for measuring oxygen concentration within an enclosed space employing an oxygen-sensitive probe according to the first aspect of the invention. The method includes the steps of (A) obtaining a transmembrane photoluminescent oxygen probe according to the first aspect of the invention, (B) adhering the probe to the exterior surface of the membrane with the first major surface of the probe facing towards the membrane, (C) allowing the oxygen concentration in sensible communication with the spot of oxygen-sensitive photoluminescent dye to equilibrate with the oxygen concentration within the space, and (D) ascertaining oxygen concentration within the enclosed space by (i) repeatedly exposing the probe to excitation radiation over time, (ii) measuring radiation emitted by the excited probe after at least some of the exposures, (iii) measuring passage of time during the repeated excitation exposures and

emission measurements, and (iv) converting at least some of the measured emissions to an oxygen concentration based upon a known conversion algorithm.

A third aspect of the invention is a method for monitoring changes in oxygen concentration within an enclosed space employing an oxygen-sensitive probe according to the first aspect of the invention. The method includes the steps of (A) obtaining a transmembrane photoluminescent oxygen probe according to the first aspect of the invention, (B) adhering the probe to the exterior surface of the membrane with the first major surface of the probe facing towards the membrane, (C) allowing the oxygen concentration in sensible communication with the spot of oxygen-sensitive photoluminescent dye to equilibrate with the oxygen concentration within the space, (D) ascertaining oxygen concentration within the enclosed space over time by (i) repeatedly exposing the probe to excitation radiation over time, (ii) measuring radiation emitted by the excited probe after at least some of the exposures, (iii) measuring passage of time during the repeated excitation exposures and emission measurements, and (iv) converting at least some of the measured emissions to an oxygen concentration based upon a known conversion algorithm, and (E) reporting at least one of (i) at least two ascertained oxygen concentrations and the time interval between those reported concentrations, and (ii) a rate of change in oxygen concentration within the enclosed space calculated from data obtained in step (D).

A fourth aspect of the invention is a method of preparing a transmembrane photoluminescent oxygen probe according to the first aspect of the invention. The method includes the steps of (A) preparing a coating cocktail which contains the photoluminescent oxygen-sensitive dye and the oxygen-permeable polymer in an organic solvent, (B) applying the cocktail to a first major surface of the oxygen impermeable support layer, (C) allowing the cocktail to dry, whereby a solid-state thin film oxygen-sensitive photoluminescent element is formed on the oxygen impermeable support layer, and (D) applying the layer of pressure-sensitive adhesive onto the first major surface of the oxygen impermeable support layer after the cocktail has dried.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a top view of one embodiment of the invention.

FIG. 2 is a cross-sectional side view of the invention depicted in FIG. 1 taken along line 2-2 with the thickness of each layer grossly enlarged to facilitate viewing of the individual layers.

FIG. 3 is a grossly enlarged cross-sectional side view of a central portion of the invention depicted in FIG. 2 with the thickness of each layer grossly enlarged to facilitate viewing of the individual layers.

FIG. 4 is a side view of the invention depicted in FIG. 1 applied to packaging.

FIG. 5 is a cross-sectional side view of a central portion of the invention depicted in FIG. 4 with the thickness of each layer grossly enlarged to facilitate viewing of the individual layers.

FIG. 6 is a top view of a second embodiment of the invention.

**DETAILED DESCRIPTION OF A PREFERRED
EMBODIMENT**

Definitions

As used herein, including the claims, the term “foodstuff” means any substance suitable for being eaten or drunk by

animals, including humans, for nutrition or pleasure, or used as an ingredient in such a substance.

As used herein, including the claims, the phrase "oxygen impermeable" means a material that has an oxygen transmission rate of less than $0.1 \text{ cm}^3/\text{m}^2 \text{ day}$ when measured in accordance with ASTM D 3985.

Nomenclature

10 Oxygen Probe

20 Oxygen Impermeable Support Layer

20a First Major Surface of Oxygen Impermeable Support Layer

20b Second Major Surface of Oxygen Impermeable Support Layer

21 Structural Substrate

22 Thin Glass Coating

30 Oxygen-Sensitive Photoluminescent Element

31 Oxygen-Sensitive Photoluminescent Dye

32 Polymer Carrier

39 Peripheral Edge of Oxygen-Sensitive Photoluminescent Element

40 Pressure Sensitive Adhesive Layer

49 Peripheral Edge of Pressure Sensitive Adhesive Layer

50 Peripheral Margin

P Hermetically Sealed Packaging

M Packaging Film or Membrane

S Retention Chamber or Space

Description

Construction and Theory of Operation

Referring generally to FIG. 4, the invention is a transmembrane oxygen-sensitive probe or sensor **10** useful for externally optically measuring oxygen concentration within an enclosed space S, such as the retention chamber S of a hermetically sealed package P. Referring generally to FIGS. 1 and 2, the probe **10** includes an oxygen impermeable support layer **20** having first and second major surfaces **20a** and **20b**, respectively, and carrying both an oxygen-sensitive photoluminescent element **30** and a layer of a pressure-sensitive adhesive **40** on the first major surface **20a**.

Without intending to be unduly limited thereby, it is believed that the probe **10** can accurately sense an oxygen concentration at the opposite side of a membrane M to which the probe **10** has been attached (i.e., transmembrane) so long as the rate at which oxygen is exchanged between the photoluminescent element **30** and the environment in communication with the surface of the membrane M to which the probe **10** is attached is at least one and preferably closer to at least two orders of magnitude less than the rate at which oxygen is exchanged between the photoluminescent element **30** and the environment in communication with the surface of the membrane M which is opposite the surface to which the probe **10** is attached. This permits the concentration of oxygen to which the oxygen-sensitive photoluminescent element **30** is exposed to equilibrate with the concentration of oxygen at the opposite side of the membrane M with minimal error introduced by oxygen reaching the oxygen-sensitive photoluminescent element **30** from the environment on the side of the membrane M to which the probe **10** is attached.

Once the probe **10** is adhered to a membrane M, oxygen is exchanged between the photoluminescent element **30** and the environment in communication with the surface of the membrane M to which the probe **10** is attached by diffusion from the backside across the support layer **20** and diffusion from the sides across the adhesive layer **40**. Diffusion across the support layer **10** can be minimized by selecting a support layer **10** that is constructed from an oxygen impermeable material (i.e., an extremely low oxygen transmission rate (OTR)). Unfortunately, this same option is not available for

minimizing diffusion across the layer of pressure-sensitive adhesive **40** as pressure-sensitive adhesives have a fairly high OTR. Hence, in order to minimize diffusion from the sides of the probe **10**, the thickness of the pressure-sensitive adhesive layer **40** should be limited so as to minimize the surface area exposed to the surrounding environment and a sizable margin **50** provided from the edge(s) **49** of the adhesive layer **40** to the edge(s) **39** of the photoluminescent element **30** to maximize the width of the adhesive between the surrounding environment and the photoluminescent element **30**.

Referring to FIG. 3, the oxygen-sensitive photoluminescent element **30** includes an oxygen-sensitive photoluminescent dye **31**, preferably embedded within an oxygen-permeable polymer carrier **32**. In order to minimize any interstitial void volume within the oxygen-sensitive photoluminescent element **30**, and thereby speed equilibration of the oxygen concentration in sensible communication with the oxygen-sensitive photoluminescent element **30** with the oxygen concentration on the other side of a membrane M to which the probe **10** is adhered, the oxygen-sensitive photoluminescent element **30** is preferably coated directly onto the support layer **20** so as to form a solid mass.

The oxygen-sensitive photoluminescent dye **31** may be selected from any of the well-known oxygen sensitive photoluminescent dyes **31**. One of routine skill in the art is capable of selecting a suitable dye **31** based upon the intended use of the probe **10**. A nonexhaustive list of suitable oxygen sensitive photoluminescent dyes **31** includes specifically, but not exclusively, ruthenium(II)-bipyridyl and ruthenium(II)-diphenylphenanthroline complexes, porphyrin-ketones such as platinum(II)-octaethylporphine-ketone, platinum(II)-porphyrin such as platinum(II)-tetrakis(pentafluorophenyl)porphine, palladium(II)-porphyrin such as palladium(II)-tetrakis(pentafluorophenyl)porphine, phosphorescent metal complexes of tetrabenzoporphyrins, chlorins, azaporphyrins, and long-decay luminescent complexes of iridium(III) or osmium(II).

Typically and preferably, the oxygen-sensitive photoluminescent dye **31** is compounded with a suitable oxygen-permeable and hydrophobic polymeric carrier **32**. Again, one of routine skill in the art is capable of selecting a suitable carrier **32** based upon the intended use of the probe **10** and the selected dye **31**. A nonexhaustive list of suitable polymers for use as the oxygen-permeable hydrophobic carrier **32** includes specifically, but not exclusively, polystyrene, polycarbonate, polysulfone, polyvinyl chloride and some co-polymers.

The support layer **20** is selected to provide sufficient structural integrity to the probe **10** and provide an oxygen impermeable barrier. The support layer **20** also needs to be transparent or translucent to radiation at the excitation and emission wavelengths of the dye **31** in the photoluminescent element **30**. Suitable materials include specifically, but not exclusively, glass, polymeric substrates **21** coated with a thin layer of glass **22**, laminates containing a layer of EVOH sandwiched between other plastics, and a relatively thick layer (i.e., several mils) of a polymer having a moderate oxygen permeability when employed as a thin film, such as PET, Nylon, PVDC (Saran), etc.

Referring generally to FIGS. 2 and 5, the probe **10** includes a layer of a pressure sensitive adhesive **40** on the first major surface **20a** of the support layer **20**—the same side as the photoluminescent element **30**—for adhering the probe **10** to the surface (unnumbered) of a membrane M—such as the exterior surface of packaging P—that defines an enclosed space or retention chamber S whose oxygen concentration is to be measured. The adhesive **40** may but preferably does not cover the luminescent element **30**.

Manufacture

The transmembrane photoluminescent oxygen probe **10** can be manufactured by the traditional methods employed for manufacturing such probes **10**. Briefly, the transmembrane photoluminescent oxygen probe **10** can be conveniently manufactured by (A) preparing a coating cocktail (not shown) which contains the photoluminescent oxygen-sensitive dye **31** and an oxygen-permeable carrier polymer **32** in an organic solvent (not shown) such as ethylacetate, (B) applying the cocktail to at least the first major surface **20a** of the oxygen impermeable support layer **20**, (C) allowing the cocktail (not shown) to dry, whereby a solid-state thin film oxygen-sensitive photoluminescent element **30** is formed on the first major surface **20a** of the oxygen impermeable support layer **20**, and then (D) applying the layer of pressure-sensitive adhesive **40** onto the first major surface **20a** of the oxygen impermeable support layer **20** using conventional coating techniques after the cocktail has dried.

Generally, the concentration of the carrier polymer **32** in the organic solvent (not shown) should be in the range of 0.1 to 20% w/w, with the ratio of dye **31** to polymer **32** in the range of 1:20 to 1:10,000 w/w, preferably 1:50 to 1:5,000 w/w.

Use

The probe **10** can be used to quickly, easily, accurately and reliably measure oxygen concentration within an enclosed space **S** without requiring placement of the probe **10** within the enclosed space **S**. Briefly, the probe **10** is used to measure oxygen concentration within an enclosed space (not shown) by (A) adhering the probe **10** to the exterior surface of the membrane **M** forming the enclosed space **S** with the first major surface **20a** of the support layer **20** facing towards the membrane **M** as depicted in FIGS. **4** and **5**, (B) allowing the oxygen concentration in sensible communication with the oxygen-sensitive photoluminescent element **30** to equilibrate with the oxygen concentration within the space **S**, and (C) ascertaining oxygen concentration within the enclosed space **S** by (i) repeatedly exposing the probe **10** to excitation radiation over time, (ii) measuring radiation emitted by the excited probe **10** after at least some of the exposures, (iii) measuring passage of time during the repeated excitation exposures and emission measurements, and (iv) converting at least some of the measured emissions to an oxygen concentration based upon a known conversion algorithm. Such conversion algorithms are well known to and readily developable by those with routine skill in the art.

In a similar fashion, the probe **10** can be used to quickly, easily, accurately and reliably monitor changes in oxygen concentration within an enclosed space **S** without requiring placement of the probe **10** within the enclosed space **S**. Briefly, the probe **10** is used to monitor changes in oxygen concentration within an enclosed space **S** by (A) adhering the probe **10** to the exterior surface of the membrane **M** with the first major surface **20a** of the support layer **20** facing towards the membrane **M** as depicted in FIGS. **4** and **5**, (B) allowing the oxygen concentration in sensible communication with the oxygen-sensitive photoluminescent element **30** to equilibrate with the oxygen concentration within the space **S**, (C) ascertaining oxygen concentration within the enclosed space **S** over time by (i) repeatedly exposing the probe **10** to excitation radiation over time, (ii) measuring radiation emitted by the excited probe **10** after at least some of the exposures, (iii) measuring passage of time during the repeated excitation exposures and emission measurements, and (iv) converting at least some of the measured emissions to an oxygen concentration based upon a known conversion algorithm, and (D) reporting at least one of (i) at least two ascertained oxygen

concentrations and the time interval between those reported concentrations, and (ii) a rate of change in oxygen concentration within the enclosed space calculated from data obtained in step (C). Again, conversion algorithms used to convert the measured emissions to an oxygen concentration are well known to and readily developable by those with routine skill in the art.

The radiation emitted by the excited probe **10** can be measured in terms of intensity and/or lifetime (rate of decay, phase shift or anisotropy), with measurement of lifetime generally preferred as a more accurate and reliable measurement technique when seeking to establish oxygen concentration via measurement of the extent to which the dye **31** has been quenched by oxygen.

I claim:

1. A method for transmembrane measurement of the oxygen concentration within a space enclosed by a membrane, comprising the steps of:

- (a) obtaining a transmembrane photoluminescent oxygen probe comprising at least (i) a transmembrane photoluminescent oxygen probe comprising an oxygen impermeable support layer carrying a spot of an oxygen-sensitive photoluminescent dye and a layer of a pressure-sensitive adhesive on a first major surface,
- (b) adhering the probe to the exterior surface of the membrane with the first major surface of the probe facing towards the membrane,
- (c) allowing the oxygen concentration in sensible communication with the spot of oxygen-sensitive photoluminescent dye to equilibrate with the oxygen concentration within the space, and
- (d) ascertaining oxygen concentration within the enclosed space by: (i) repeatedly exposing the equilibrated probe to excitation radiation over time, (ii) measuring radiation emitted by the excited probe after at least some of the exposures, (iii) measuring passage of time during the repeated excitation exposures and emission measurements, and (iv) converting at least some of the measured emissions to an oxygen concentration based upon a known conversion algorithm.

2. The method of claim **1** wherein the oxygen impermeable support layer on the transmembrane photoluminescent oxygen probe has an oxygen transmission rate of less than 0.1 cm³/m² day.

3. The method of claim **1** wherein the layer of pressure-sensitive adhesive on the transmembrane photoluminescent oxygen probe is less than 0.8 mm thick.

4. The method of claim **1** wherein (i) the adhesive layer on the transmembrane photoluminescent oxygen probe has a peripheral edge, (ii) the spot of oxygen-sensitive photoluminescent dye on the transmembrane photoluminescent oxygen probe has a peripheral edge, and (iii) the probe has a peripheral margin of at least 2 mm from the peripheral edge of the spot of oxygen-sensitive photoluminescent dye to the peripheral edge of the adhesive layer that completely surrounds the spot of oxygen-sensitive photoluminescent dye.

5. The method of claim **1** wherein the space is a retention chamber of a hermetically sealed package containing an oxygen labile pharmaceutical or foodstuff.

6. A method for monitoring changes in oxygen concentration within a space enclosed by a membrane, comprising the steps of:

- (a) obtaining a transmembrane photoluminescent oxygen probe comprising at least (i) a transmembrane photoluminescent oxygen probe comprising an oxygen impermeable support layer carrying a spot of an oxygen-sen-

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- sitive photoluminescent dye and a layer of a pressure-sensitive adhesive on a first major surface,
- (b) adhering the probe to the exterior surface of the membrane with the first major surface of the probe facing towards the membrane,
- (c) allowing the oxygen concentration in sensible communication with the spot of oxygen-sensitive photoluminescent dye to equilibrate with the oxygen concentration within the space,
- (d) ascertaining oxygen concentration within the space over time by: (i) repeatedly exposing the equilibrated probe to excitation radiation over time, (ii) measuring radiation emitted by the excited probe after at least some of the exposures, (iii) measuring passage of time during the repeated excitation exposures and emission measurements, and (iv) converting at least some of the measured emissions to an oxygen concentration based upon a known conversion algorithm, and
- (e) reporting at least one of (i) at least two ascertained oxygen concentrations and the time interval between those reported concentrations, and (ii) a rate of change in

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oxygen concentration within the enclosed space calculated from data obtained in step (d).

7. The method of claim 6 wherein the oxygen impermeable support layer on the transmembrane photoluminescent oxygen probe has an oxygen transmission rate of less than 0.1 cm³/m² day.

8. The method of claim 6 wherein the layer of pressure-sensitive adhesive on the transmembrane photoluminescent oxygen probe is less than 0.8 mm thick.

9. The method of claim 6 wherein (i) the adhesive layer on the transmembrane photoluminescent oxygen probe has a peripheral edge, (ii) the spot of oxygen-sensitive photoluminescent dye on the transmembrane photoluminescent oxygen probe has a peripheral edge, and (iii) the probe has a peripheral margin of at least 2 mm from the peripheral edge of the spot of oxygen-sensitive photoluminescent dye to the peripheral edge of the adhesive layer that completely surrounds the spot of oxygen-sensitive photoluminescent dye.

10. The method of claim 6 wherein the space is a retention chamber of a hermetically sealed package containing an oxygen labile pharmaceutical or foodstuff.

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